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DATA AVAILABILITY, DATA QUALITY IN LCA

Methodology for systematic analysis and improvement of manufacturing unit process life-cycle inventory (UPLCI) —CO_2PE! initiative (cooperative effort on process emissions in manufacturing). Part 1: Methodology description

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Abstract
Purpose This report proposes a life-cycle analysis (LCA)-oriented methodology for systematic inventory analysis of the use phase of manufacturing unit processes providing unit process datasets to be used in life-cycle inventory (LCI) databases and libraries. The methodology has been developed in the framework of the CO_2PE! collaborative research programme (CO2PE! 2011a) and comprises two approaches with different levels of detail, respectively referred to as the screening approach and the in-depth approach.
Methods The screening approach relies on representative, publicly available data and engineering calculations for energy use, material loss, and identification of variables for improvement, while the in-depth approach is subdivided into four modules, including a time study, a power consumption study, a consumables study and an emissions study, in which all relevant process in- and outputs are measured and analysed in detail. The screening approach provides the first insight in the unit process and results in a set of approximate LCI data, which also serve to guide the more detailed and complete in-depth approach leading to more accurate LCI data as well as the identification of potential for energy and resource efficiency improvements of the manufacturing unit process. To ensure optimal

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Preamble. The CO_2PE! UPLCI—Initiative aims to document and improve the environmental impact created during the use phase of a wide range of discrete part manufacturing processes. This article is the first of two and describes the developed methodology comprising two approaches with different levels of detail. The second paper provides for both approaches a case study of the Life Cycle Inventory step.

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reproducibility and applicability, documentation guidelines for data and metadata are included in both approaches. Guidance on definition of functional unit and reference flow as well as on determination of system boundaries specifies the generic goal and scope definition requirements according to ISO 14040 (2006) and ISO 14044 (2006).
Results The proposed methodology aims at ensuring solid foundations for the provision of high-quality LCI data for the use phase of manufacturing unit processes. Envisaged usage encompasses the provision of high-quality data for LCA studies of products using these unit process datasets for the manufacturing processes, as well as the in-depth analysis of individual manufacturing unit processes.
Conclusions In addition, the accruing availability of data for a range of similar machines (same process, different suppliers and machine capacities) will allow the establishment of parametric emission and resource use estimation models for a more streamlined LCA of products including reliable manufacturing process data. Both approaches have already provided useful results in some initial case studies (Kellens et al. 2009; Duflou et al. (Int J Sustain Manufacturing 2:80–98, 2010); Santos et al. (J Clean Prod 19:356–364, 2011); UPLCI 2011; Kellens et al. 2011a) and the use will be illustrated by two case studies in Part 2 of this paper (Kellens et al. 2011b).

Keywords CO_2PE! · Energy and resource efficiency · Manufacturing process impact · Methodology · Process emission · Unit process life-cycle inventory (UPLCI)

1 Introduction

The Ecoinvent database, as supplied by the Ecoinvent Centre (Ecoinvent 2011), is one of the most widely consulted sources of consistently and transparently documented life-cycle inventory (LCI) data. In this database, in contrast to materials and chemicals production, manufacturing processes, as used for discrete part manufacturing, are unfortunately less well documented in terms of the overall environmental impact. On the one hand, the coverage of the wide range of available manufacturing processes is rather limited to more conventional processes such as drilling, turning, milling, etc. Commonly used processes, such as, for example, electrical discharge machining and rapid prototyping processes, are lacking in the database. On the other hand, most of the available data on manufacturing processes are incomplete: the focus is often limited to theoretical energy consumption, and data on potential process emissions are rarely found (Steiner and Frischknecht 2007).

Another available source of LCI data are input–output databases. Among others, examples can be found for the USA (Suh 2003), Denmark (Weidema et al. 2005), The Netherlands (Goedkoop 2004) and Japan (Toshiba 2006). The disadvantage of IO databases for LCA is that processes are aggregated, i.e. at the level of product groups rather than individual products. Consequently, the impact of individual manufacturing processes cannot be extracted from this category of data.

Furthermore, organisations such as the International Iron and Steel Institute (Global Steel 2010), the European Aluminium Association (EAA 2008) and Plastics Europe (Plastics Europe 2010) provide extensive LCI data for respectively steel, aluminium and plastic half products, while the BUWAL database (2011) covers a wide range of packaging materials. Despite the very useful work of the respective sector organisations, the scope of these LCI databases is typically limited to primary material production (e.g. sheets, foils, etc.) and recycling processes.

Finally, also some international institutions and organisations provide information on life-cycle thinking-based data, tools, and services. Examples can be found in the ELCD database of the European Commission (ELCD 2011) and the Life-Cycle Initiative launched by the United Nations Environment Programme and Society of Environmental Toxicology and Chemistry (UNEP-SETAC 2011). Since the main objective of these organisations is the exchange and distribution of LCI data to a wide audience; they mainly count on the channels mentioned above for the real LCI data development.

The lack of thorough analysis of manufacturing processes results in optimisation opportunities often not being recognized. The fact that newly emerging, non-conventional production processes are increasingly energy intensive (Gutowski et al. 2006) strengthens the need for reliable and statistically rigid data sets. Therefore, both LCA practitioners and eco-designers have a growing need for reliable data on the environmental impacts of manufacturing processes. This concerns the availability of the data, the quality of the data (recent data, data completeness, etc.) as well as the usefulness of the data format (presented in a way that the data can be used by LCA experts and designers, respectively). There is also an obvious need to demonstrate the growing impact of the manufacturing stage on the overall life cycle of products towards policy makers. The CO_2PE!-Initiative (CO_2PE! 2011a) has as an objective to coordinate international efforts aiming to document and analyse the environmental impacts of a wide range of current and emerging manufacturing processes, and to provide guidelines to reduce these impacts. A proposed two-level approach is aimed at both providing manufacturing unit process datasets for LCA of products manufactured in multi-unit process plants and at supporting the important diagnosis and optimization of the environmental impact of specific manufacturing unit processes.

By applying the two-level methodology described throughout this paper consistently on a range of similar

machines (several suppliers and machine capacities), parametric emission estimation models can be established for each manufacturing process and a measure for the variability can be obtained. In combination with parametric process time models, the production emissions and material input for any product can be predicted. An optimal ratio between the amount of required input data and corresponding accuracy of the results is a target here.

2 CO_2PE!—framework

Based on a systematic taxonomy of manufacturing unit processes (DIN8580 2003; Gibovic and de Ciurana 2008; CO_2PE! 2011b), a worldwide data collection effort is proposed within the CO_2PE! UPLCI—initiative. Figure 1 gives an overview of the CO_2PE UPLCI—framework to collect, document and provide LCI data for a wide range of discrete manufacturing unit processes as well as to identify the potential for environmental improvements of the involved machine tools.

Below, the different steps of this framework are specified:

A. Locate the intended manufacturing unit process(es) in the DIN 8580 based CO_2PE!—taxonomy.

B. Register the intended contribution to the selected taxonomy branch in order to allow comparison of output between similar efforts.

C. Select and follow one of the approaches defined in the CO_2PE!—methodology (described in Section 3) to generate and collect LCI data of the indicated manufacturing unit process(es). Besides the basic screening approach (mainly based on engineering calculations) and the in-depth approach (mainly based on industrial process measurements), also a combination of both approaches can be used, provided that each step is clearly documented.

D. Provide the generated LCI data to the CO_2PE!—core team for peer review, after which the data could be included in the CO_2PE!—UPLCI—database.

E. Where relevant, LCI data exchange and comparison can occur between partners with overlapping interests. This step can take place either before or after peer review.

F. Evidently, some of the steps (e.g. C, D, E and H) could lead to individual as well as joint publications providing wider visibility of the results.

G. If the in-depth approach is followed (partially or completely), potential for environmental improvements (increase of energy and/or resource efficiency, emission reductions) could be investigated for the involved

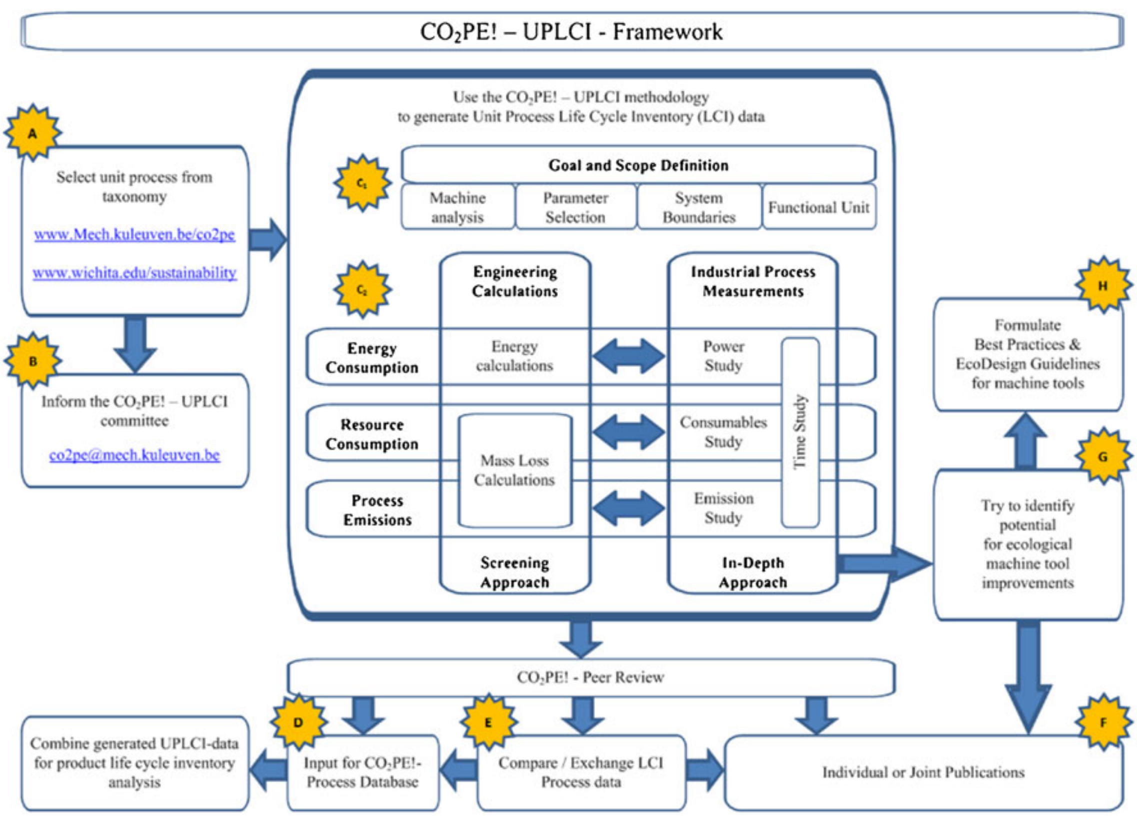


Fig. 1 Overview of the CO_2PE! UPLCI—framework

manufacturing unit process(es) and corresponding machine tool(s).

H. It is an explicit aim to formulate best practices and eco-design guidelines for the investigated processes and range of machine tools based on the identified improvement potentials of step G.

3 Methodology

The LCA-oriented (ISO 14040 (2006) and ISO 14044 (2006)) methodology applied in the CO_2PE!—initiative is described in this section. Since guidance on the goal and scope definition is crucial in view of generating generic life cycle data sets, this paper concentrates on these two phases (Section 3.1) and the subsequent collection and documentation of inventory data (Section 3.2). The impact assessment and interpretation steps are outside the scope of this paper.

3.1 Goal and scope definition

First the goal and scope of the study should be clearly defined and must be consistent with the intended unit process. The most important aspects, which are described more in detail below, to be considered are the system boundaries and the functional unit of the intended process. Furthermore, both the machine tool architecture and the most influential process parameters are investigated and all sub-processes and production modes are identified and located.

The CO_2PE!—template (Section 3.3) can be used complementarily to a written report and should enhance consistency in goal and scope definition for all intended studies.

The goal of the data collection effort is to supply well-documented information (best practice rules) and experimental data for LCI data sets of manufacturing processes to be used in different LCA applications. In addition, the data must also be applicable to identify Key Environmental Performance Indicators of the investigated machine tool(s) in support of eco-design at a machine tool builder level and/or LCA. Hence, the target audience covers LCA practitioners performing life-cycle studies of manufacturing processes in product systems as well as machine tool designers and manufacturing process specialists.

The data collected should allow subsequent impact assessment using the most common impact assessment methodologies including CML 2001, Eco-indicator 99, EDIP, ReCiPe, IMPACT2002, etc. Since our collection of inventory data (emissions, use of energy and resources) should cover all relevant impact categories of the intended impact assessment methodology, the covered impact categories (e.g. climate change, ecotoxicity, resource depletion, etc.) are specified as part of the scope definition.

The collected data sets are not intended for comparative assertions disclosed to the public, unless decided otherwise by the collectors of the data. In the latter case, the unit processes to be compared should have the same functional unit and the data providers must assure compliance to the additional mandatory requirements of ISO 14044 (2006) on the execution, documentation, review and reporting of the LCI/LCA study. Furthermore, possible financing organisations shall be explicitly mentioned.

To ensure the worldwide applicability of the LCI data obtained within the CO_2PE!—initiative, the location and associated climatic factors of the measurements should be clearly documented. The additivity property needed for sequences of unit processes to manufacture a product requires that a fixed thermodynamic state be set for all inputs and outputs, unless clear industrial practice is different. The default input and output state is at 25°C and an atmospheric pressure of 101.3 kPa. An exception example could be molten steel to enter a casting process. Of course, in this case an UPLCI to obtain molten steel from solid room temperature steel billets or iron ore would also be needed. Similarly, the date (e.g. year) of the analysis will be indicated.

3.1.1 System boundaries

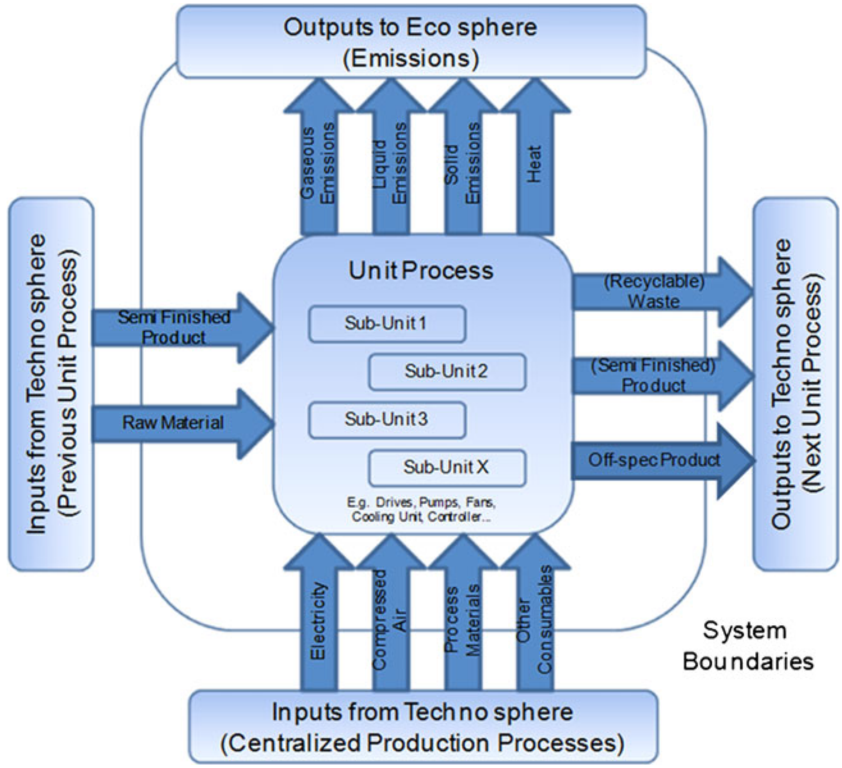
The system boundary determines which unit process shall be investigated and which sub-processes (at which level of detail) for the selected unit process will be investigated. The omission of inputs or outputs is only recommended if it does not significantly change the overall conclusions of the study. If some flows (or sub-processes) are explicitly excluded from the scope of the study, this must be clearly stated in the report as it will differ among various UPLCI and may be improved as more data become available.

In a general production process, consisting of a sequence of unit processes, the different unit processes and their inter-relationships should be described to define where each intended unit process starts, which operations take place and where the unit process ends. Therefore, all included in- and outputs from techno as well as ecosphere must be listed as shown in Fig. 2.

Besides studies at machine tool level, also more extensive studies on sub-unit level can be performed, e.g. in support of eco-design guidelines and machine tool design optimisation in a later stage.

For CO_2PE! UPLCI studies, the system boundaries are set to include only the operating phase (the use stage) of the unit process, disregarding the rest of the life cycle (materials processing, production and disposal) of the machine tool itself. Inputs and outputs required for the

Fig. 2 System boundaries of a unit process



means of infrastructure, including land occupation and transformation, are consequently excluded. Furthermore, the transport of machine tools, equipment as well as consumables is not included, but should be taken into account when a full product LCA is performed with use of the UPLCI data.

Since the analysis focuses on normal working conditions, exceptional events, such as accidents, which can have very dramatic ecological impacts, but occur only seldomly (e.g. generated waste by failure of the energy supply), are not considered. Nevertheless, incidents happening on a regular basis (e.g. off-specification products) are taken into account in the life-cycle inventory.

As shown in Fig. 2, the functioning of the manufacturing machine (unit process) is isolated, disregarding the influence of other elements of the general production process, such as prior and subsequent unit processes, material handling systems and feeding robots, and centralized production stations for consumables such as electricity, compressed air, process materials (gasses, lubricants, etc.), cooling circuits, etc. To the maximum extent, the inputs and outputs are modelled as flows from or to the surrounding techno sphere, and quantified as such: e.g. electricity consumption in kilowatt hour, compressed air in cubic metre at a given pressure, etc. If relevant and possible, these flows should be supplemented with the related flows from and to the ecosphere (e.g. input of resources and emissions to the environment). Similarly, waste heat is documented as an output to techno sphere in view of allowing future allocation, for example, potentially reduced heating requirements for production halls, but the allocation is not performed yet in the basic LCI.

3.1.2 Functional unit

The functional unit, which must be clearly defined (quantitatively as well as qualitatively) and measurable, serves to define a reference flow to which all other input and output flows of the process quantitatively relate. A functional unit must provide a unique basis for comparison between different process alternatives (ISO14040 2006; ISO14044 2006; JRC 2010; Pennington et al. 2010). In the case of machining datasets where material is removed during processing, nowadays the functional unit is typically the amount of material removed (weight or volume). Other functional units could be the amount of processing needed to process a part (with certain dimensions) during full or partial load operations. In most cases, individual datasets per type of material processed have to be developed.

For manufacturing process analysis, different functional units could be defined based on process, material and geometric characteristics (e.g. material thickness).

Within the CO_2PE!—initiative, we propose to use a generally applicable reference flow of 1 s of processing time for a specified load level of a unit manufacturing process for a specified material, based on a working scheme of 2,000 h/year (250 days with one shift of 8 h and the process start-up/shutdown takes place just before/after the

shift starts). The system boundaries include the actual machining time (full-power mode and/or partial-power mode with given %) as well as an allocated part of the non-productive modes (standby mode, start-up mode, shutdown mode and off mode). In this way, almost all inputs and outputs could be related to this reference flow (with exception of produced waste and off-spec products). Based on the reference flow, the manufacturing process contribution to the environmental impacts of a product can be predicted on the basis of expected theoretical processing time. An example is provided in Part 2 of this article.

Besides this generally applicable reference flow, a functional unit needs to be defined in relation to the investigated process. This functional unit should allow LCA practitioners to draw the proper extent of the process. The geometric characteristics of the reference workpiece can be both of the incoming material (as in machining processes) and of the outgoing component (as in injection moulding). An example of a functional unit for laser cutting processes can be defined as 1 m of laser cutting with a certain laser source (e.g. CO_2, YAG, fibre, etc.) at full load of a certain material with a certain sheet thickness. Each process could have different data series for all processed materials for the total load (full-power mode) as well as for each partial load. For processes with no discrete loads, the most common or average levels could be applied.

3.1.3 Parameter selection

A manufacturing unit process is converting material/chemical inputs into a transformed material/chemical output. During these transformational changes, the involved machine tool consumes both energy (e.g. electricity, steam and direct fuel) and materials, ancillaries or resources (e.g. process gasses, lubricants and filters) and generates direct emissions (e.g. air emissions, solid waste and off-spec parts). In this section, the parameters or conditions of the input that govern these LCI characteristics as well as the generated characteristics in the output product are listed based on available process experience and literature. Some parameters are strongly correlated to the created environmental impact while others are of minor importance, but may be vital in a product quality sense. Therefore, the list of parameters is ranked, in an approximate way, from largest to least effect. As much as possible relevant parameters are investigated successively during the different steps of the process LCI described in Section 3.2.

3.1.4 Machine analysis

The machine tool architecture is investigated before the actual inventory analysis for the machine tool takes place. The typical use scenarios of the machine tool are considered and the energy and resource consuming units (ECUs) as well as the emission generating sub-processes of the machine tool under investigation are identified together with their function, within the overall machining operation, and location.

Since the final database will consist of average process or technology values as well as values for specific process ranges (e.g. best available technologies) or even individual machine types, the studied machine tools should be described and situated in their process category.

The first focus of the analysis is on machine tools used for large series manufacturing operations. This is defined as the use of processes that generally have high automation and are at the medium to high throughput production range compared with all other machines that perform a similar operation. A high production basis for machine analysis is consistent with the life-cycle goal of estimating energy use and mass losses (energy and resource efficiency) representative for efficient product manufacturing.

3.2 Inventory

After the goal and scope definition, relevant data are collected during the inventory phase. As shown in Fig. 1, this data collection can be performed in two different ways and includes an energy, resource and process emission study. The screening approach could be seen as a fast (e.g. requiring a time investment order of magnitude of a couple of hours to a few days), first description of the unit process and leads to approximative LCI data. The in-depth approach (e.g. typically implying a data collection effort of 1 to 2 weeks), whether or not based on the screening approach, includes a time, power, consumables and an emission study and provides more accurate and complete LCI data that will help identify the potential for improvements of the involved manufacturing unit processes. Besides these approaches, also a combination of both approaches could be used, provided that each step is clearly documented. After the data collection, the environmental impacts of a process can be determined and interpretations can be made. Required data depend on the goal and scope of the study, and may include a mixture of measured, calculated or estimated data.

3.2.1 Screening approach

In the screening approach (using rules of engineering and industrial practice), for each uplci, data are gathered following the generic methodology for each manufacturing unit process that has been developed by Overcash et al. (2009) utilizing the earlier work of Murphy et al. (2003), Gutowski et al. (2006), EBM (2010), and Overcash (1995).

As shown in Fig. 1, first the goal and scope definition is documented. Besides the four main topics: system boundaries, functional unit, parameter selection and machine analysis, this includes also the necessary process information (e.g. brief process description, schematic overview and photograph of the unit process) and literature study (e.g. peer reviewed papers, reports, university design problems and solutions, equipment manufacturing data and domain expert consultations).

The inventory phase is mainly divided in two parts, namely the energy and mass loss calculations (UPLCI 2011).

- LCI energy calculations

Using sets of equations (possibly correlations as well as rules of practice) and tables of data from external sources, basic working relationships are developed between the recognizable priority parameters and the energy use. The total energy is determined based on a functional unit output and typically consists of two parts. The first part is the direct, incremental energy to accomplish the unit process task, like metal removal in machining. The second and often most important part is the fixed energy from auxiliary systems active during idling (partial full mode and standby). Energy evaluation and calculations should thus evaluate both of these contributions. In high production analysis, start-up energy is generally very low per unit of product.

- LCI mass loss calculations

In an analogous fashion to the energy calculations, the mass loss is determined from a list of selected primary parameters. Mass losses can be basic materials (such as metal loss from the drilled hole); auxiliary chemicals (such as cutting fluid); unit process malfunctioning or other imperfections that lead to off-specification product rejection, etc. as can be estimated from statistical information. These results must be related to the major governing parameters of the unit process (such as type of material processed). The heuristics calculation should show an approximate mass balance for the unit process.

Supplementing the LCI-analysis, an example is to be provided for a representative material/chemical input and with a transparent description of the corresponding unit process heuristic. The example should describe how basic material properties can be traced in literature and used in obtaining the results.

A substantial number of case studies using this screening approach can be found on the website of the Wichita State University (UPLCI 2011). Furthermore, an example is provided in Part 2 of this paper (Kellens et al. 2011b).

3.2.2 In-depth approach

The in-depth approach, whether or not based on the screening approach, may identify focus points for machine tool improvement based on the results that it generates. It includes a time, power, consumables and emission study and leads to more accurate and complete LCI data, and supports the identification of potentials for environmental and economic improvements of the studied manufacturing equipment. Figure 3 shows an overview of the process inventory phase for the in-depth approach.

Time study During the first step of the in-depth approach, time studies will be performed in order to identify the different production modes of a machine tool and their respective shares in the covered time span. A time study is based on observations of different production environments (companies) for multiple full shifts including start-up and shutdown phases. The identified modes start from the machine tool start-up, over the use phase to finally switching off the machine. Six main production modes are selected and listed in Table 1. Depending on the process, these main production modes could be expanded with one or more additional (other) production modes.

The share of all selected energy and/or resource consuming units in the total scope of each respective production mode will be investigated in the next step.

Power (energy) study Since energy use is determined by the supplied power multiplied by the duration of an operation, the consumed electrical power should be measured for all identified production modes. After the various production modes of a specific process are identified during the time study, these are subsequently scrutinised by measuring the power consumption of the complete machine tool as well as of all relevant ECUs active in each production mode.

It is important to measure the throughput of the unit process over the time that power measurements are taken (e.g. number of holes drilled, length of weld, etc.).

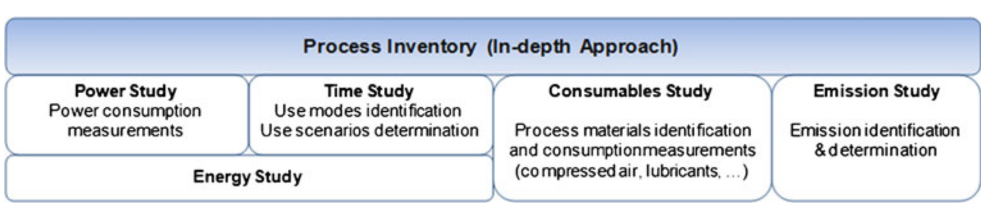


Fig. 3 Overview of the process inventory phase for the in-depth approach

Table 1 Production modes overview

Number	Production mode
A	Start-up mode
B	Full-power mode
C	Partial-power mode
D	Standby mode
E	Shutdown mode
F	OFF mode
G	Other mode(s)

To obtain a good overview of the individual power consumption of each ECU in each production mode, the total input power of the machine tool (reference) and the power consumed by the specific ECU can be measured simultaneously in all modes. Both power meters could be controlled simultaneously by a computer system which is also responsible for the data logging. In order to ensure representative results, all measurements should be performed in an ambient temperature between 20°C and 25°C. In addition, the total machine power (in kW or hp) listed for the unit process machine tool will be documented to help understand the percent of rating for typical operations (e.g. nominal power levels).

Equation 1 shows the formula to calculate the energy consumption for the reference flow (1 s of time in processing time or equivalent) which includes productive production modes (full-power mode or partial-power mode, standby mode and other modes) as well as non-productive production modes (start-up mode, shutdown mode and off mode) for a single 8-h shift per day working scheme. An average energy consumption is calculated for each individual production mode, but each individual power level and time (distribution) of the different production modes will also be reported to assure greater transparency.

This formula is based on a working scheme of 2,000 h/year (250 days with one shift of 8 h and the process start-up/shutdown takes place just before/after the shift starts).

It is the experience of the authors that the choice of power measurement equipment can significantly influence the registered power levels. For this reason, a short description of recommended measuring equipment and the used measurement principle is provided in Appendix I of the Electronic supplementary material. Furthermore, Kara et al. (2011) present an overview of the evolution and the latest developments in electricity metering and monitoring systems. An exemplary list of metering devices is given to demonstrate how features of the different measurement instruments can be matched for certain measurement tasks in different application levels.

$$E_{\mathrm{re}} = \frac{P_{\mathrm{m}} + \left(\sum_{i=1}^{\mathrm{m}} \left(P_i * \frac{T_i}{T_{\mathrm{m}}}\right) + \left(\frac{\left(P_{\mathrm{s}} * \frac{T_{\mathrm{s}}}{3{,}600}\right) + \left(P_{\mathrm{e}} * \frac{T_{\mathrm{e}}}{3{,}600}\right)}{8}\right) + P_{\mathrm{off}} * \left(\frac{\left(16 - \left(\frac{T_{\mathrm{s}} + T_{\mathrm{e}}}{3{,}600}\right)\right) + \left(\frac{115 * 24}{250}\right)}{8}\right)\right)}{3,600} \tag{1}$$

With:

- E_{re} Average energy consumption for the reference flow (functional unit; kWh/s)
- P_{m} Average power during full- or partial-power mode (kW)
- T_{m} Time share of full- or partial-power mode (%)
- P_i Average power during other individually productive production modes i (kW)
- T_i Time share of other individually productive production modes i (%)
- P_{s} Average power during the start-up mode (kW)
- T_{s} Time of start-up mode (s)
- P_{e} Average power during the shutdown mode (kW)
- T_{e} Time of shutdown mode (s)
- P_{off} Average power during the off mode (kW)

Consumables study In parallel with the time and power measurements, consumables (materials, components, semi-products and ancillaries) are measured in each production mode. Examples of consumables are: compressed air, lubricants, process gasses (N_2, O_2, etc.) and process filters. The total material flow (determined by the product design and equal for all processes in a comparative study) is not relevant for a UPLCI, but the generated amount of waste is process dependent and included as consumable in our study. Furthermore, the raw material type and its dimensions must be documented, as these are relevant for the process and considered in the reference flow as well as the functional unit. Since the production of the wasted material, as well as the recycling, combustion or landfilling impact of this amount of waste, need to be taken into account when the UPLCI data are used in the modelling of a product LCI, it should be noted that the waste recyclability must be clearly indicated. The total amount of these 'consumables' is determined directly (volume and weight) or indirectly (flow metres in combination with the time study). Also, these data on consumables must be linked to the number of workpieces or operations conducted by the unit process.

All consumables should be expressed per reference flow and therefore in mass or volume units per second (e.g. l/s, g/s and m^3/s) with exception of the created waste, which will be expressed as percentage of input materials (raw materials as well as (semi-finished) products). If the consumables are only provided during the full- or partial-power modes, the consumption of this consumable during the reference flow (1 s of time in process or equivalent) is equal to the consumption of the full- or partial-power mode. If the consumption is divided over multiple modes, the consumption rate of the functional unit will be calculated using an expression similar to Eq. 1.

Emission study Parallel to the power and consumables measurements, where relevant (e.g. where a mass balance shows abnormalities or where the nature of the used or formed substances indicates a contribution to one of the impact categories included in the scope definition) an emission measurement needs to be performed for each production mode. Gaseous, liquid and solid emissions (e.g. unrecyclable waste material), whether or not included in coolant, lubricants or process medium, as well as heat must be taken into account and will be expressed in the relevant unit per second (e.g. mg/s).

Air emissions can be divided into aerosol and particle emissions as well as gas emissions, and are expressed in volume units (part per million and part per billion) or in weight per volume (in mg/m^3, usually at 20°C and 1 atm (101.3 kPa)). Emissions may take place both to the indoor environment (leading to potential occupational exposure) and to the external environment (leading to potential environmental exposure). The inventory compiles flows of mass per reference flow or functional unit. If concentration measurements are performed, these must be integrated over time to obtain the mass emission.

Possible emission measuring methods are summarized in the second part of Appendix I of the Electronic supplementary material, which starts with a discussion concerning the analysis of air emissions and ends with a brief discussion of other types of emissions.

3.3 Data handling and presentation

3.3.1 CO_2PE!—template

To understand and use the collected data in a correct way, the data content and the way in which it was obtained should be clearly defined. A template for the in-depth approach is prepared to provide all necessary background information as well as the collected LCI datasets in a uniform and efficient way. Based on the input form, the reference flow and a schematic process overview will be automatically generated. Furthermore, a resulting form will be created. Besides this template, which is available online as Electronic supplementary material and illustrated by a case study in Part 2 of this paper, it is recommended to provide a written report including a case study for each UPLCI, showing a clear relation to the data estimated (for the screening approach) or measured and presented in tables (for the in-depth approach).

3.3.2 Confidentiality

The involvement of a sufficiently large number of partners will assure an appropriate, statistical approach, covering multiple suppliers and machine tool types and capacities as well as process–material combinations for every studied manufacturing process. As such the credibility of the outcome of the effort will be high. By merging and comparing unit process datasets of similar machine tools of different suppliers and capacities provided by different CO_2PE—partners, generic unit process datasets and parametric models will be generated based on the average values of the different studies. Where relevant, further divisions (process capacities, material, etc.) per manufacturing unit process will be made. The use of these generic datasets also guarantees the confidential handling of the individually collected machine specific industrial process data.

3.3.3 Data dissemination

Once the generic unit process dataset(s) for a certain manufacturing process is/are prepared, they will be converted to the EcoSpold data format (EcoSpold 2011), which is the most widespread LCI data exchange format worldwide, supported by all leading LCA software tools such as Gabi, SimaPro and Umberto

4 Conclusions and outlook

By providing a well-defined methodology, it is the aim of the authors to give an impetus to the generation of uniform, complete and robust unit process inventories. The CO_2PE!—template is available to accurately define the goal and scope definition of the intended study, as well as for the dissemination of the unit process inventory results.

The collected data for a broad range of manufacturing unit processes will lead to an extensive unit manufacturing process database which can be used by LCA experts, eco-designers and product developers for analysing the environmental impact of individual manufacturing unit processes as well as complete production chains. This will improve the current deplorable situation where publicly available LCI databases lack unit process data for most manufactur-

ing processes and where the quality of what is available is often quite deficient. By repeating this study for a range of similar machines (several suppliers and machine capacities), parametric impact estimation models and eco-design rules for machine tools, which can be used by LCA experts and product developers, can be established, and estimates of the variability across different machine types verified. Furthermore, in-depth studies on sub-process level will lead to identification of process improvement opportunities directly related to the architecture and control logic of the investigated machine tools.

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